Intern. J. Neuroscience, 117:1167–1184, 2007

ISSN: 0020-7454 / 1543-5245 online
DOI: 10.1080/00207450600934655

informa
healthcare

DIFFERENCES IN EEG BETWEEN GIFTED AND AVERAGE STUDENTS: NEURAL COMPLEXITY AND FUNCTIONAL CLUSTER ANALYSIS

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The main aim of the present study was to assess the differences in EEG between gifted and average students. Another aim of the present study was to investigate which brain areas are related to a Rey-Osterrieth complex figure (ROCF) memorizing using a functional cluster (FC) analysis and how the complexity of cortical activities changes in both gifted and average students. The EEG was

Received 4 January 2006.
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recorded from 16 electrodes in both 18 right-handed healthy gifted and age-matched average students before and during ROCF memorizing. FC was estimated to characterize the joint interactions among many brain regions and neural complexity. The study assessed the visuo-spatial memory abilities through examining EEG profiles using the measure of FC, and planning and executive function using recall score. The gifted students made a significantly high score compared to the average students during ROCF memorizing. Both groups showed very different FC patterns. ROCF memorizing is related to the visual mental process, thus simultaneous neuronal activities appears on the right central, temporal, occipital, and bilateral prefrontal regions. One of the notable characteristics of gifted students' FC map is the dominance of the right hemisphere compared with that of average students, and it is accordance with the characteristics of gifted brain.

Keywords functional cluster analysis, gifted students, neural complexity, Rey-Osterrieth complex figure test

INTRODUCTION

An EEG is a time series of electrical potentials representing the sum of a large number of neuronal dendritic potentials in the brain so that it provides a continuous recording of brain activity (Gazzaniga et al., 2002). Many studies have been reported the correlation between intelligence and EEG (Jaušovec, 1997; Jaušovec & Jaušovec, 2000; Schmid et al., 2002). The EEG amplitude or power studies generally report a positive correlation between absolute power and IQ (Marosi et al., 1999; Schmid et al., 2002). Schmid et al. (2002) supposed that the IQ is correlated with the degree of EEG maturation and thus reflects the active number of synapses and the degree of differentiation of the neuronal controlling system based on the strong relationship between spectral EEG parameters and the degree of intelligence. Gifted individuals exhibited a higher hemispheric activation in EEG during problem preparation than problem solving (Jaušovec, 1997).

The coherence measure of EEG reports a correlation between neural complexity and intelligence. Negative correlation between EEG coherence and IQ especially in the frontal lobes have been reported (Barry et al., 2002; Martin-Loeches et al., 2001; Silberstein et al., 2004) and increased dimensionality of the EEG is reported as being positively correlated with IQ in the eyes closed resting condition (Anokhin et al., 1999).

Although many studies suggested the correlation of intellectual abilities and EEG, joint functional interactions among many brain regions during cognitive function have not been explored. FC analysis provides a more useful tool to characterize the joint interactions between many brain regions than convenient coherence analysis, which only provides the relation between the two different areas. The brain regions belonging to the same cluster were all functionally involved, whereas the regions belonging to separate clusters were presumably functionally unrelated, in an experimental paradigm or group of subjects (Tononi et al., 1998). The application of their approach had been tested on positron emission tomography (PET) data obtained from schizophrenics and normal controls performing a set of cognitive tasks, and these results showed distinct differences of clustering between the two groups (Tononi et al., 1998). Jin et al. (2004; Jin et al., 2005) showed that FC analysis would be a potential tool to investigate the simultaneous neuronal activity of human EEGs as well as neuroimaging technique like PET. In addition, neural complexity, C_N, is a measure that should reflect the interplay between functional segregation and integration within a whole neural system (Tononi et al., 1994; Tononi & Edelman, 1998). The present study used neural complexity measure to investigate the changes of brain activities.

ROCF test (Osterrieth, 1944; Rey, 1941) is a neuropsychological test extensively used in clinical practice to investigate visuo-spatial constructional function, visuo-graphic memory, and some aspects of planning and executive function (Caffarra et al., 2002), and has been used widely in neuropsychological assessment of perceptual organization, visuo-spatial constructional ability, and nonverbal memory. One of the critical aspects of this test is that organizing the figure into meaningful perceptual units during copy enhances its subsequent free recall from memory (Deckersback et al., 2000). There were moderate linear relationships between executive function and memory measures (Anderson et al., 2001). In general, scores on this test reflect the examinees' visual organization and motor planning skills (Demsky et al., 2000) and this test is quite useful with obtaining knowledge about a wide variety of cognitive processes and functions. The present study assessed visuo-spatial memory abilities through examining EEG profiles using the measure of FC, and planning and executive function by means of recall score. The study used the ROCF test in order to identify the differences in EEG between gifted and average students. The study investigated which brain areas are related to the ROCF memorizing by means of FC analysis and how the complexity of cortical activities changes in both gifted and average students.

Giftedness is defined as some special endowment or propensity for creativity, skill, and eminent achievement, found in relatively few individuals among the population (Chen & Buckley, 1988). Renzulli (2000) referred to two categories of giftedness. "Schoolhouse giftedness" might be called test-taking or lesson-learning giftedness that measured by IQ or other cognitive ability tests, and it can be identified through standardized assessment techniques. "Creative-productive giftedness" describes those aspects of human activity and involvement where a premium is placed on the development of original material and products that are purposefully designed to have an impact on one or more target audiences. Here, the study's attention was restricted to the creative-productive giftedness in gifted students, who scored high on Torrance tests of creative thinking (TTCT) and IQ tests.

MATERIALS AND METHODS

Participants

Gifted students were 18 healthy right-handed middle school volunteers (age: 13 years, 10 males and 8 females) without any neurological or psychiatric disease and with normal EEG. These students belong to Science Education Institute for the Gifted at Chonbuk National University, South Korea, which provides them with an advanced science education. The major goal at the Institute is to identify especially gifted students in the fields of science, mathematics, and information science, and to provide them with an extremely high and excellent education. They were selected through both a selective written examination and advanced oral test among the recommended students from their school. They basically showed the general characteristics of giftedness as well. Here, TTCT that was less affected by the social and cultural heritage was used to distinguish creative-productive giftedness students from average ones. Whomever has scored more than 119 in the creativity index on TTCT is regarded as a gifted student. Table 1 presents the results of TTCT.

EEG recordings were also obtained from 18 right-handed and age-/sex-matched average middle school students (age: 13 years, 11 males and 7 females) who were healthy volunteers with no history of psychiatric or neurological diseases. Gifted and average students also showed significantly different IQ scores (Table 2).

The handedness of all subjects was classified according to hand preference when writing a sentence. All subjects and their parents were fully informed and consented to participate in the study and the local ethical committee approved this study.

Experimental Procedure

An experimenter explained the whole experiment procedure and cautioned in detail with attaching electrodes on the scalp. EEG recordings were made in an electrically shielded room, where students were seated in a comfortable chair.

Table 1. Results of TTCT

Factors	Group	Mean	SD	T	p
Fluency	Average	96.25	15.14	−6.296	0.000***
	Gifted	125.42	13.71		
Originality	Average	102.90	20.85	−6.127	0.000***
	Gifted	135.58	11.30		
Abstractness of Titles	Average	87.95	32.63	−1.223	0.229
	Gifted	100.95	33.73		
Elaboration	Average	71.40	16.78	−2.559	0.015*
	Gifted	85.21	16.92		
Resistance to Premature Closure	Average	91.55	21.78	−3.617	0.001**
	Gifted	113.79	16.02		
Checklist of Creative Strengths	Average	11.85	4.86	−2.823	0.008**
	Gifted	15.58	3.17		
Creativity Index	Average	101.40	22.25	−4.491	0.000***
	Gifted	128.16	13.72		

$^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$.

Students were told that their EEG would be recorded while they rested and performed a task. After electrodes had been attached by the experimenter, a 5-min adaptation period was observed before the first recording. Subsequently, EEG was recorded in an artifact-free recording period of 1 min as a resting EEG. They were instructed to close their eyes and relax, and not to move around excessively during the recording.

Then students were told that they would be shown ROCF in a piece of paper (A4 size, 210 × 297 mm) for 1 min and that they were to copy that figure using a pencil provided onto another sheet of blank paper (A4 size, 210 × 297 mm) after a 1 min memorizing process. ROCF is composed of overlapping squares, rectangles, triangles, and various other shapes. They draw that figure from memory as carefully and as accurately as they can and no time limit was

Table 2. Means and Standard Deviation (SD) for IQ

Group	Mean	SD	T	p
Average	115.16	10.84	4.123	0.000***
Gifted	128.61	8.58		

$^{***}p < .001$.

imposed. Second segments of EEG recordings were performed when students were memorizing the figure for 1 min.

EEG Acquisition

The EEGs were recorded from the 16 scalp loci (F7/8, T3/4, Fp1/2, F3/4, C3/4, P3/4, O1/2, and T5/6) of the international 10—20 system using a Medelec (TECA, England). All leads were referenced to linked ear lobes (A1 and A2) and a ground electrode was applied to the forehead. Electrode impedance was maintained below 5 kΩ. The time constant was 0.1 s and the sampling frequency was 256 Hz. Sixty seconds of data were recorded at each monitoring stage and digitized by a 12-bit analog-to-digital converter in an IBM PC. All data were digitally filtered at 0.3–60 Hz, and each EEG record was judged by inspection to be free from electro-oculographic and movement artifacts and to contain minimal electro-myographic activity. Artifact-free EEG recordings of 4,096 data points (16 s) were used for the analysis.

FC Analysis and Neural Complexity

FC analysis provides a useful tool to characterize the joint interactions of different elementary subsystems, x_i with $I = 1, \ldots, N$, of the whole brain system X, consisting of a collection of N (the number of EEG electrodes) elementary subsystems. The authors computed the cluster index $CI(X_j^k)$ (Tononi et al., 1998) to identify FC by measuring for many different subsets as follows:

$$CI\left(X_j^k\right) = \frac{I\left(X_j^k\right)}{MI\left(X_j^k; X - X_j^k\right)}$$

where X_j^k indicates a jth subset composed of k components of system X, and $X - X_j^k$ is its complement. $MI(X_j^k; X - X_j^k)$ indicates mutual information that represents interactions between X_j^k and $X - X_j^k$, and $I(X_j^k)$ denotes the integration of X_j^k, which represents a multivariate measure of statistical independence among the elements X_j^k. $I(X_j^k)$ is a measure for deviation from statistical independency of the individual components, that is, integration has a maximum value when the elements of a subset are completely dependency; and, if the elements are statistically independent, the integration is zero.

The mutual information $MI(X_j^k; X - X_j^k)$ is calculated as $MI(X_j; X - X_j^k) = H(X_j^k) + H(X - X_j^k) - H(X)$, where $H(X_j^k)$, $H(X - X_j^k)$ and $H(X)$ are entropies of X_j^k and $X - X_j^k$ considered independently, and that of the system considered as a whole, respectively (Papoulis, 1991). $I(X_j{}^k)$ is calculated as the difference between the sum of the entropies of all the individual components $x_{j,i}(1 \leq i \leq k)$ of $X_j{}^k$ considered independently, and the entropy of $X_j{}^k$ considered as a whole (Tononi et al., 1994).

$$I\left(X_j^k\right) = \sum_{i=1}^{k} H(x_{j,i}) - H\left(X_j^k\right)$$

where $X_j{}^k$ is a jth subset composed of k elementary components $x_{j,i}$ of the system X. The indices j, i $(1 \leq i \leq k)$ denote the indices of the elementary components, that is the index j refer to which subset of k components is considered, i labels the particular component of that subset: $X_j^k = \{x_{j,i} 1 \leq i \leq k\}$. Assuming that the multidimensional stationary stochastic process that describe the activity of the k subsystems of the whole brain system X is Gaussian, the entropy is just $H(X^k) = 0.5\,1\,\mathrm{n}(2\pi\,\mathrm{e})^k|\mathrm{COV}(X^k)|$, with |.| indicating the matrix determinant, and $\mathrm{COV}(X^k)$ the covariance matrix of X^k (Tononi et al., 1998). In the present study, the integration and mutual information were calculated using the entropy according to the aforementioned definition for the mean removed (zero-mean) EEG data set, and so the EEG signal was considered as a multivariate Gaussian signal, in agreement with computation of integration in previous researches (Tononi et al., 1998; Putten & Stam, 2001).

The study calculated the *CI* values for all 16 channels of EEG recordings obtained from all subjects. Calculation of *CI* values for each subject was performed for each subset of the collection of subsets with size k, that is composed of k-out-of-16 components, over the 16!/k!(16-k)! combinations of the k components by definition of *CI*. For instance, if a subset is chosen from $16!/4!(16-4)!(=1820)$ composed of $k = 4$, as described in Figure 1, the *CI* value is calculated in the earlier definition using the integration between them (gray-colored area) and the mutual information between these 4channels and the rest of the 12 channels.

Figure 2 shows the average mutual information and integration as a function of subset size of one of the EEG data sets.

Neural complexity, C_N, is defined in terms of integration $CN(X) = \sum_{k=1}^{N}(k/n)I(X) - I(X_j^k)$ as given in Tononi et al. (1994). Figure 3 illustrates the neural complexity of one of the EEG sets, utilizing the ensemble average of integration values for subsets composed of increasing numbers of subset size (the oblique lined area). C_N is high when the integration of the system is high and at the same time the average integration for small subsets is lower than would be expected from a linear increase over increasing subset size (Tononi

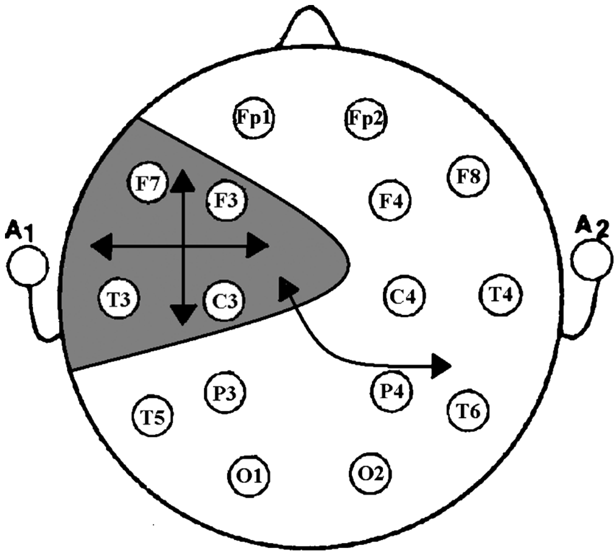

Figure 1. Shematic map of cluster. The diagram shows an example of a subset composed of $k =$ 4, the *CI* value was calculated using the integration (cross arrows) between F3, F7, T3, and C3 (gray-colored area) and mutual information (curved arrow) between these 4 channels and the other 12 channels (white area).

et al., 1994). Thus, high values of complexity reflect the coexistence of a high degree of functional specialization and functional integration within a system such as the brain (Tononi & Edelman, 1998).

Statistical Analysis

The statistical significance of *CI* values is assessed by computing a Student's *t*-like parameter, t_{CI}, given by Tononi et al. (1998):

$$t_{CI} = \frac{CI\left(X_j^k\right) - \left\langle CI(X_H^k)\right\rangle}{std(CI(X_H^k))}$$

where $CI(X_j{}^k)$ is *CI* of the *j*th system of a subset size *k*, $\langle CI(X_H{}^k)\rangle$ is the mean of the *CI* distribution for the subset size *k* accumulated from many (here, 100) sampled equivalent homogeneous systems, and $std(CI(X_H^k))$ is the standard deviation of the distribution. The parameter X_H (the null hypothesis) denotes a homogeneous system that has the same overall integration but without any FCs (Tononi et al., 1998).

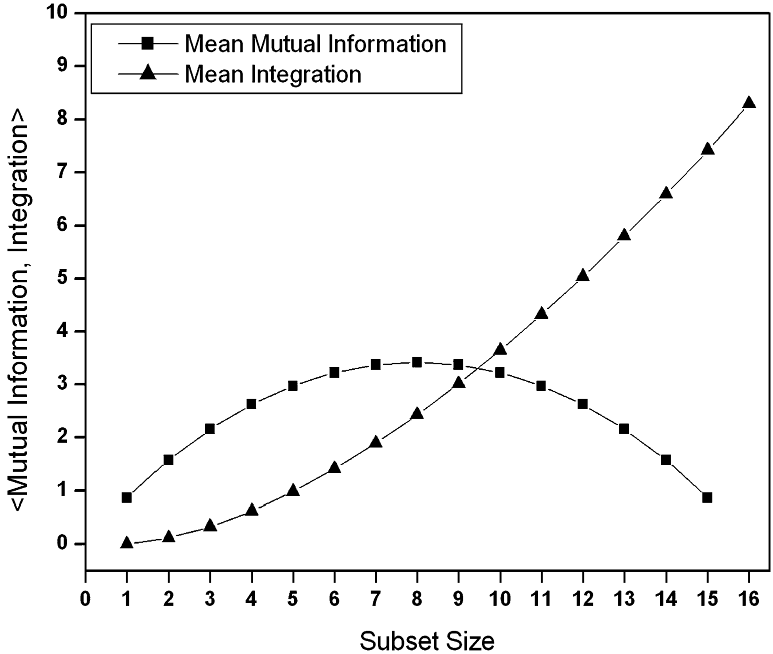

Figure 2. Mean values of integration and mutual information as a function of a subset size for one EEG recording (solid line). Symbols, square and triangle, indicates the average integration and mutual information, respectively.

In the present study, the confidence level is $p < .01$, because 100 null systems were used in order to gauge the likelihood of obtaining a given *CI* of no FC is present. Statistical process is designed to test the null hypothesis that the signal consists of non-clustered homogeneous system, and the t_{CI} value is higher than zero when the null hypothesis is rejected.

After all the calculations, including t_{CI}, the authors then chose the statistically significant subset (here, $p < .01$), with the largest *CI* value among all the possible subsets and with a result higher than 1. This subset was chosen because a *CI* much greater than 1 indicates a subset of elements that are strongly interactive between themselves. A weighted cluster distribution was constructed using the elements of the statistically significant subsets for all the subjects. For example, if the F7, F3, T3, and C3 channels were elements of the statistically significant subset, then these locations were respectively weighted by 1 unit. This process was repeated for all the subjects. A weighted cluster distribution (by the number of involved locations) could then be obtained for

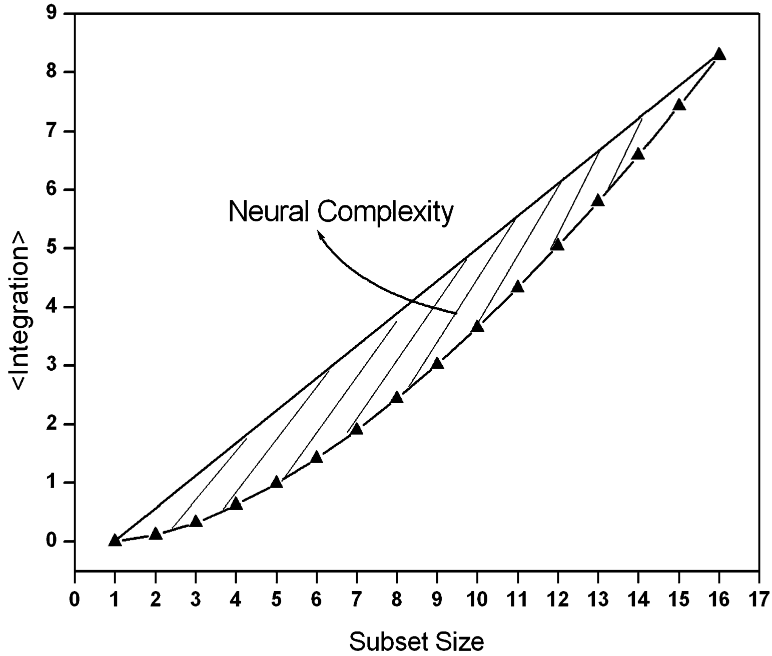

Figure 3. Definition of neural complexity. Neural complexity (oblique lined area) is a measure that should reflect the interplay between functional segregation and integration within a whole neural system.

a given task and a given group of subjects. The study used a weighted cluster distribution to draw a topographic cluster map at the scalp location. Because the extracted elements from the respective subjects were statistically significant, the weighted distribution constructed by those elements could show the group properties of a given task.

The detailed description is presented in Tononi et al. (1998) and Jin et al. (2004; 2005).

Results of neural complexity were examined statistically using a two-way analysis of variance (ANOVA) with Condition (rest and ROCF memorizing, 2 levels) serving as within subjects factor, and Group (gifted and average students, 2 levels) serving as between subjects factor. Paired Student's t-test (SPSS 6.0) was used as a post-hoc analysis to evaluate the statistical differences in neural complexity between different conditions with the threshold significant level $p < .05$.

Table 3. Results of recall score of ROCF test

Test	Group	Mean	SD	T	p
ROCF test	Average	18.38	7.40	−2.097	0.047*
	Gifted	21.63	5.85		

$^{*}p < .05$.

RESULTS

Neuropsychological Results

Table 3 displays the result of recall score of ROCF test. Unpaired t-test results show the significant high score in gifted students during ROCF memorizing.

Neural Complexity

An ANOVA yielded significant main effects for the Condition factor ($F(2,34) = 10.79$, $p = .000$) in gifted students. Paired t-test results show the significant increased neural complexity during ROCF memorizing. No significant effects were found in the remaining ANOVA. The F-tests are reported in Table 4. Figure 4 presents the neural complexity for gifted and average students in different conditions.

FC Analysis

Figure 5 displays a topographic cluster map for both gifted and average students in rest and ROCF test conditions. Before the mental task, for gifted students the left-right frontal, temporal, and occipital areas were synchronous neuronal groups, in contrast, the cluster for average students was concentrated

Table 4. F-tests for differences in neural complexity between the gifted and average students in two different conditions

	Condition	p-value
Gifted students	$F\ (1, 17) = 10.790$	0.000***
Average students	$F\ (1, 17) = 0.711$	0.498
	Group	p-value
Resting	$F\ (1, 17) = 1.536$	0.232
ROCF test	$F\ (1, 17) = 2.698$	0.119

$^{***}p < .001$.

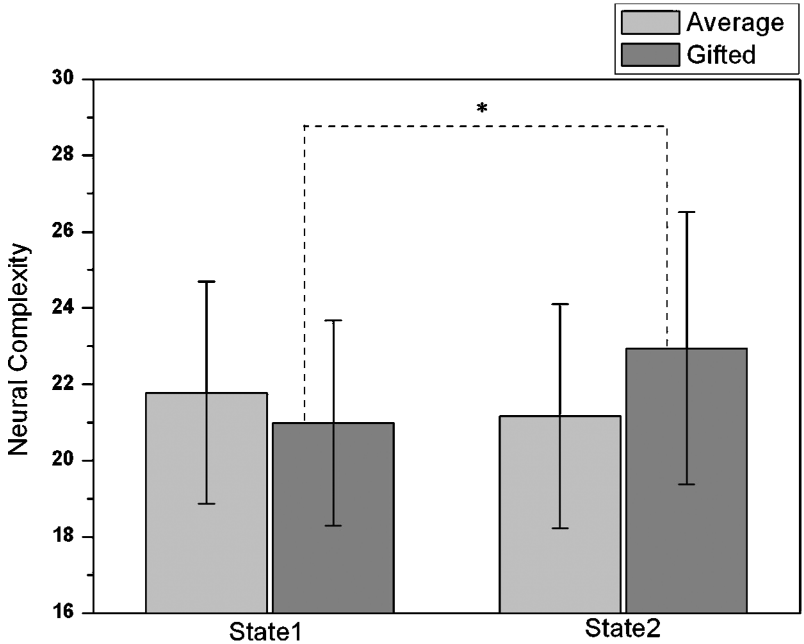

Figure 4. Changes of the neural complexity for the different conditions. X-axis indicates before (State1) and during ROCF memorizing (State2), respectively. Y-axis denotes neural complexity values. Significantly increased complexities during ROCF memorizing are detected in gifted students ($*p < .05$).

on the left frontal, central, and parietal areas. During ROCF memorizing, gifted individuals displayed more cooperation in the right central, temporal, occipital and bilateral prefrontal areas than average ones did.

A topographic cluster map was drawn at the scalp location using a weighted cluster distribution. As is conventional, the nose is the top of all figures. The same gray color scale from light gray (minimum) to dark gray (maximum) was used on the appropriate scalp locations to indicate their weighted cluster values for each figure. Values between electrodes were linearly interpolated.

DISCUSSION

The present study assessed whether the differences in EEG between gifted and average students exist or not during ROCF memorizing by means of using FC and neural complexity measures.

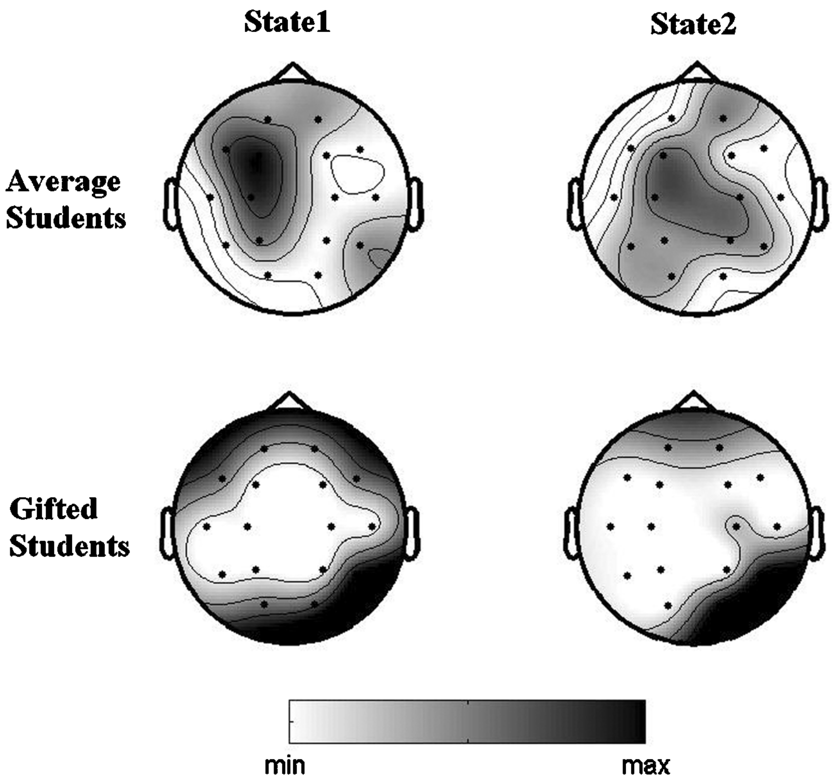

Figure 5. Before the mental task, for gifted students the left-right frontal and temporo-occipital areas were synchronous neuronal groups, in contrast, the cluster for average students concentrated on the left frontal, central, and parietal areas (State1). During ROCF memorizing, the elements of cluster for giftedness were changed to the right central, temporo-occipital and bilateral prefrontal areas (State2).

First of all, the results presented that gifted students revealed a greater recall performance than average students and the amount of information was increased during mental task compared with the baseline only for gifted students. Neural complexity that reflects the functional specialization and integration provides a measure for the amount of information that is integrated within a neural system (Tononi et al., 1998), so high values of complexity stand for the coexistence of a high degree of functional specialization and integration. Increased complexities also suggest that distributed neural process underlying conscious experiences must be functionally integrated and highly differentiated at the same time (Müller et al., 2003). Several EEG network studies have argued that increased complexity and increased neural efficiency are positively related to intelligence (Anokhin et al., 1999; Jaušovec & Jaušovec, 2003; Neubauer et al., 2004).

In addition, ROCF test are moderate linear relationships between executive function and memory measures (Anderson et al., 2001). And recall scores on this test reflect the examinees' visual organization, motor planning skills (Demsky et al., 2000), and this test is quite useful with obtaining knowledge about a wide variety of cognitive processes and functions. Taken altogether, the results reflect the efficiency of cognitive functioning and information processing of gifted brain.

Secondly, the study showed the different patterns of FCs depending on the task and group. Functionally involved cortical areas during ROCF memorizing distributed over the right central, temporal, occipital, and bilateral prefrontal areas in gifted students, whereas average students revealed somewhat different pattern.

ROCF test is a neuropsychological test extensively used in clinical practice to investigate visuo-spatial constructional function, visuo-graphic memory (Caffarra et al., 2002). Many researches related to the visual mental imagery process indicated the role of temporal and occipital areas in mental tasks (Pihlajamaki et al., 2000; Zago et al., 2001; Fell et al., 2000; Laeng & Teodorescu, 2002; Mast & Kosslyn, 2002). Farah et al. (1989) reported that the mental imaging of visual stimuli produced a change in the latency of the first negative component of the Event Related Potential (ERP) recorded over the occipital and posterior temporal regions of the scalp. The visual areas subserving visual imagery are parieto-occipital and temporo-occipital visual association areas (Roland & Gulyas, 1994). Eye movements during mental imagery and, more importantly, that these eye movements are functionally involved in mental imagery processes (Laeng & Teodorescu, 2002; Mast & Kosslyn, 2002), and primary visual cortex excitability increased during visual mental imagery (Sparing et al., 2002). Thus, the right temporal and occipital regions cooperative functional interactions in gifted students are related to the visual imagery process during ROCF memorizing.

The prefrontal cortex mediates higher-order mental abilities such as flexible and innovative thinking, and planning, judgment, and decision making based on new or updated information (Fuster, 1989; Roland, 1993; Frith & Dolan, 1996). Previous imaging studies have shown that spatial working memory tends to activate the right prefrontal cortex (McCarthy et al., 1994). The right prefrontal cortex may have a special role in memory retrieval or attention (Gazzaniga et al., 2002; Coull et al., 1996). Thus, the involvement of the bilateral prefrontal areas in gifted students during ROCF memorizing may suggest the spatial working memory, memory retrieval or attention.

Taken together, ROCF memorizing is related to the visual mental process, thus simultaneous neuronal activities appears on the right central, temporal, occipital, and bilateral prefrontal regions.

One of the notable characteristics of gifted students' FC map is the dominance of the right hemisphere compared with that of average students. According to O'Boyle et al.'s (1995) work, enhanced right hemispheric involvement during basic information processing, as well as superior coordination, and allocation of cortical resources within and between hemispheres, are unique characteristics of the gifted brain. Hence, the results support the right hemisphere dominancy of gifted students' brain.

Conventional coherence measure provides electrical relations between different areas; however, one can draw out the multiple regions having the strongly and simultaneously integrated regions between many brain regions using FC analysis. Although FC does not show the direct relationship between scalp-recorded electrical and neuronal activities in the underlying cortical tissue, the simultaneous neuronal activity could be investigated through the application of FC analysis. The present results may be helpful in understanding the differences between gifted individuals and average ones, and measures used in the present results would be useful tool to identify them. The extension of a FC analysis to an EEG experiment with higher spatial resolution and the use of various experimental protocols would lead to a better understanding of characteristics of giftedness.

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